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## PROGRESSIVE COLLAPSE TESTING OF RELOCATABLE TROOP BARRACKS

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14. ABSTRACT The U.S. Air Force, U.S. sister services, coalition partners, and agencies face an on-going elevated threat level from attacks, whether by force or explosion, from both foreign and domestic enemies. As the US establishes and maintains airbases to provide support around the globe, we are challenged to protect our planes, our equipment - and above all else - the lives of our personnel. The attacks may include rockets and mortars, which may lead to damaged facilities that employ relocatable construction techniques. This test program aimed to assist in managing some risk factors for CONEX-based relocatable structures. Specifically, this program focused on progressive collapse of CONEX-based relocatable structures as a result of an attack using an explosive weapon. Analysis of a typical relocatable barracks is briefly discussed followed by a review of column removal testing; finally results are presented from a 155-mm artillery shell detonation against the barracks. Ultimately, the reader should realize as a result of this work that progressive collapse of CONEX-based relocatable barracks as described in Unified Facilities Criteria is not a concern when constructed per the method presented in this paper.				
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## TABLE OF CONTENTS

LIST OF FIGURES .....	ii
LIST OF TABLES.....	iii
1. SUMMARY .....	1
2. INTRODUCTION .....	2
2.1. Background.....	2
3. ANALYSIS CONFIGURATION .....	6
4. ANALYSIS RESULTS .....	13
5. TEST ARTICLE CONSTRUCTION .....	14
6. COLUMN REMOVAL TESTING.....	21
7. EXPLOSIVE TEST .....	23
8. CONCLUSIONS.....	24
LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS.....	26

## LIST OF FIGURES

Figure 1. Typical CONEX-based Relocatable Barracks .....	2
Figure 2. Exploded View of Typical CONEX Shipping Container .....	3
Figure 3. 3 × 3 × 2 Test Article Rendering – Isometric View .....	6
Figure 4. Column Removal Locations (Shaded Red).....	6
Figure 5. Corrugated Sheathing Elements.....	7
Figure 6. Corrugated Sheathing Segment Section Properties (KN, mm).....	8
Figure 7. (a) Weldable Base Twistlock (b) Vertical Twistlock (c) Horizontal Twistlock .....	8
Figure 8. (a) Front Corner Post (b) Rear Corner Post .....	9
Figure 9. Section Designs for Corner Posts with CSI SAP2000® (a) Front Corner Post (b) Rear Corner Post .....	9
Figure 10. Tie–Force Plate Approximately 12.7 mm Thick of Unknown Grade.....	10
Figure 11. CONEX Twistlock Scheme Top View (Floors and Roof Hidden).....	10
Figure 12. Typical Container Twistlock Connections.....	11
Figure 13. Weldable Twistlock to Baseplate Detail .....	11
Figure 14. CONEX Relocatable Barracks Test Article CSI SAP2000® Model.....	12
Figure 15. Worst-case Column Removal Location (a) Iso View (b) Elevation View.....	13
Figure 16. CONEX Container General Condition upon Delivery to Tyndall AFB .....	14
Figure 17. Window Opening Cut out by AFCEC Contractors.....	15
Figure 18. Hydraulic Jacking Detail for Test .....	15
Figure 19. Column Splice Rendering .....	16
Figure 20. Hydraulic Crib Jack.....	16
Figure 21. (a) Typical Rear Corner Post Splice (b) Typical Front Corner Post Splice .....	17
Figure 22. Foundation Plan View.....	17
Figure 23. Rebar Layout Plan View .....	18
Figure 24. (a) Formed Concrete Spread Footer (b) Pump Truck Extended to Spread Footers.....	19
Figure 25. Rendering of Sand Simulating Live Loads .....	19
Figure 26. Sand Being Loaded into Sandbox .....	20
Figure 27. Construction Sequence.....	20
Figure 28. Completed Relocatable Barracks Test Article .....	21
Figure 29. Hydraulic jack schematic set up.....	21
Figure 30. Hydraulic power unit.....	22
Figure 31. (a) Shoring Installed (b) Column Segments Removed (c) Hydraulic Jacks Inserted .....	22
Figure 32. Column Removal Test Location Nomenclature.....	23
Figure 33. 155-mm Artillery Shell Placement.....	24
Figure 34. Damage to Barracks from Detonation of a 155-mm Artillery Shell.....	24

## LIST OF TABLES

	<b>Page</b>
Table 1. Loading Criteria.....	12
Table 2. Column Removal Test Results .....	23

## 1. SUMMARY

CONEX-based relocatable barracks are a common sight at many U.S. and coalition bases worldwide. Cost effective, readily available, and robust, CONEX containers can be stacked and connected together and modified in such a way as to create relocatable barracks for troops and other base personnel. While CONEX-based structures are a quick and effective means to provide shelter to troops from the environmental elements a large uncertainty existed as to how those barracks would respond to a sudden column loss. The U.S. Department of Defense evaluated CONEX-based barracks for progressive collapse per Unified Facilities Criteria (UFC) and determined a substantial risk to progressive collapse existed and that a structural retrofit was needed to bring CONEX-based barracks into compliance with UFC. However, due to uncertainty in assumptions made during structural analysis such as fixity provided at CONEX-to-CONEX connections, CONEX-to-ground connections, and rigidity provided by corrugated sheathing the U.S. Air Force Civil Engineer Center (USAFCEC) had concerns regarding the validity of preliminary structural findings indicating progressive collapse concerns. USAFCEC commissioned a program to perform dynamic full-scale column removal tests of a CONEX-based relocatable barracks structure matching specifications exactly from a similar facility currently in theater. The program consisted of three distinct phases. Phase 1 was a preliminary structural analysis using CSI SAP2000® to determine response of the CONEX-based structure to column removal at various locations. Phase 2 was to construct a representative test article and perform a controlled dynamic testing regimen utilizing a system of hydraulically controlled structure jacks to document structure response to sudden column removal. Phase 3 was to detonate a 155-mm artillery shell in contact with the structure at the area deemed most critical during phase 2 and measure the structural response. The results of the program indicate no progressive collapse concerns as described by the UFC exist to CONEX-based relocatable barracks structures currently in theater when constructed to the specifications documented in this paper.

## 2. INTRODUCTION

### 2.1. Background

CONEX-based relocatable barracks can be found in a number of U.S. military and coalition force installations worldwide. The desire to construct relocatable barracks utilizing CONEX shipping containers is reasonable considering the depth of knowledge of handling and stacking that exists within the U.S. and coalition forces. That depth of knowledge comes from the sheer number of containers that are required to mobilize forces and support wartime activity. As recently as 2013 there were 92,566 twenty-foot-equivalent units (TEU)<sup>1</sup> on the ground in Afghanistan alone. Figure 1 shows a typical CONEX-based relocatable barracks.



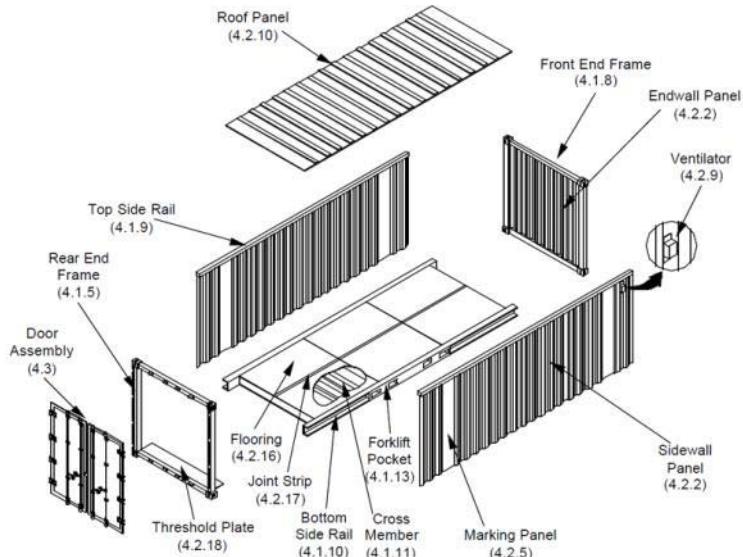
**Figure 1. Typical CONEX-based Relocatable Barracks**

Figure 1 shows a three-story U.S. military barracks facility. The number of barracks similar to Figure 1 currently in place is difficult to ascertain due to unavailable inventory documentation. The barracks structure, placed on concrete foundations, is approximately 7.8 m to the eave and consists of CONEX containers with external dimensions of 6.058 m (Length)  $\times$  2.438 m (Width)  $\times$  2.591 m (Height). Each connection is made using an International Organization for Standardization (ISO)-compliant twistlock. CONEX containers and twistlocks adhere to the following specifications. Figure 2 shows exploded view of CONEX parts referenced in specifications listed below.

#### 1. Material specifications:

- 1.1 Roof panels, door panels, side panels, front panels, bottom side rails, cross members, upper and lower plates of forklift pockets, rear corner posts (outer), door sill, door header (upper and lower), door horizontal frames, door vertical frames, top side rails, front corner posts, front bottom end rail, front top end rail are all crafted from anti-corrosive Steel: CORTEN A, SPA-H, B480 or equivalent, Y.P. 35 kg/ mm<sup>2</sup>, T.S. 49 kg/ mm<sup>2</sup>.
- 1.2 Rear corner posts are made from rolled high-tensile steel: SM490A, or equivalent, Y.P. 33 kg/mm<sup>2</sup>, T.S. 50 kg/mm<sup>2</sup>.

1.3 Floor center rail is made from structural steel: SS400, Y.P. 25 kg/mm<sup>2</sup>, T.S. 41 kg/mm<sup>2</sup>.  
 1.4 Corner fitting is made of casted weldable steel: SCW480, Y.P. 28 kg/mm<sup>2</sup>, T.S. 49 kg/mm<sup>2</sup>.  
 1.5 Twistlocks adhere to ISO 3874:1997/Amd.1:2000(en).



**Figure 2. Exploded View of Typical CONEX Shipping Container**

## 2.1 General specifications:

2.1.1 The containers are constructed with steel frames, fully vertical-corrugated steel sides and front wall, horizontal-corrugated steel double doors at rear end, die-stamped steel roof and corner fittings.

2.1.2 All welds of exterior, including the base frames, are continuous welding using CO<sub>2</sub> gas, but inner part of each bottom side rail will be fastened by staggered stitch welding.

2.1.3 Interior welds — when needed — will be stitched with a minimum bead length of 15 mm.

2.1.4 Gaps between adjacent components to be welded will not exceed 3 mm or the half-thickness of the parts being welded.

2.1.5 Chloroprene sealant is to be applied at periphery of floor surface and inside unwelded seams, butyl sealant is used to caulk at invisible seam of floor joint area and between door gasket and frame.

2.1.6 The wooden floor will be fixed to the base frames by zinc-plated self-tapping screws.

## 2.2 Protrusions

2.2.1 The plane formed by the lower faces of the bottom side rails and all transverse members shall be positioned by 12.5 mm  $\pm$  1.5 mm above the plane formed by the lower faces of the bottom corner fittings.

2.2.2 The top corner fittings are to protrude a minimum of 6 mm above the highest point of the roof.

2.2.3 The outside faces of the corner fittings will protrude from the outside faces of the corner posts by minimum 4 mm for side structure and 4 mm for front end structure.

2.2.4 The outside faces of the corner fittings will protrude from the side wall by nominal 8 mm and from the outside face of the end wall by 8 mm.

2.2.5 Under maximum payload, no part of the container will protrude below the plane formed by the lower faces of the bottom corner fittings at the time of maximum deflection.

2.2.6 Under  $1.8 \times$  maximum gross weight, no part of the container will protrude more than 6.0 mm below the plane formed by the lower faces of the bottom corner fittings at the time of maximum deflection.

2.3 Corner fittings: The corner fittings will be designed in accordance with ISO 1161 and manufactured at the works approved by classification society.

2.4 Base frame structure: Base frame will be composed of two (2) bottom side rails, a set of forklift pockets and eighteen (18) cross members.

2.4.1 Bottom side rail: Each bottom side rail is built of  $48 \times 158 \times 30 \times 4.5$ -mm thick cold-formed channel section steel made in one piece. The floor guide rails of 3.0-mm thick pressed angle section steel are provided to the bottom side rails by staggered stitch welding. The lower flange of the bottom side rail is outward to facilitate easy removal of the cross members during repair and lower susceptibility to corrosion. Reinforcement plates are to be made of 4.0-mm thick, flat steel plates. The plates are welded to bottom corner fitting.

2.4.2 Forklift pockets: Each forklift pocket is built of 3.0-mm thick full-depth flat steel top plate and two 200-mm deep  $\times$  6.0-mm thick flat lower end plates between two channel section cross members.

2.4.3 Cross member: The cross members are made of pressed channel section steel with a dimension of  $45 \times 122 \times 45 \times 4.0$  mm for the normal areas and  $75 \times 122 \times 45 \times 4.5$  mm for the floor butt joints. The cross members are placed fully to withstand floor strength and welded to each bottom side rail.

2.5 Flooring: The floor will consist of six pieces plywood boards, floor center rail, and self-tapping screws.

2.5.1 Floor: The wooden floor to be constructed with 28-mm thick 19-ply hardwood plywood boards are laid longitudinally on the transverse members between the steel floor center rail of 4.0-mm thick flat bar and the 3.0-mm thick pressed angle section steel floor guide rails stitch welded to the bottom side rails. The floorboards are tightly secured to each transverse member by self-tapping screws, and all butt-joint areas and peripheries of the floorboards are caulked with sealant.

2.5.1.1 Wood species: Apitong or Keruing

2.5.1.2 Glue: Phenol-formaldehyde resin.

2.5.1.3 Treatment: Preservative: BASILEUM SI-84 or others. b) Average moisture content will be 12% before installation.

2.5.2 Self-tapping screw: Each floor board is fixed to the transverse members by zinc-plated self-tapping screws that are 8.0-mm dia. shank  $\times$  16-mm dia. head  $\times$  45-mm length, and fastened by four screws per cross member but five screws at joint areas. Screw heads are to be countersunk through about 2 mm below the floor top surface.

2.6 Rear frame structure: The rear frame will be composed of one door sill, two corner posts, one door header and four corner fittings, which will be welded together to make the doorway.

2.6.1 Door sill: The door sill to be made of a 4.5-mm thick pressed open section steel is reinforced by four internal gussets of a 4.0-mm thickness at the back of each locking cam keeper location. The upper face of the door sill has a 10-mm slope for better drainage. A 200- $\times$  75-mm section is cut out at each end of the door sill and reinforced by 200- $\times$  75-mm channel steel as a protection against handling equipment damages.

2.6.2 Rear corner post: Each rear corner post of hollow section is fabricated with pressed, 6.0-mm thick, steel outer part and 40- $\times$  113- $\times$  12-mm hot-rolled channel section steel inner part, which are welded continuously together to ensure a maximum width of the door opening and to give a sufficient strength against stacking and racking forces. Four (4) sets of hinge pin lugs are welded to each rear corner post.

2.6.3 Door header: The door header is constructed with a 4.0-mm thick pressed "U" section steel lower part having four internal gussets at the back of each locking cam keeper location and a 3.0-mm thick pressed steel upper part, which are formed into box section by continuous welding.

2.7 Roof structure: The roof is constructed with five corrugated (die-stamped) steel panels and four corner protection plates.

2.8 Roof panel: The roof panel is constructed with 2.0-mm thick die-stamped steel sheets having about 6.0 mm upward smooth camber, which are welded together to form one panel and continuously welded to the top side rails and top end rails. All overlapped joints of inside unwelded seams are caulked with chloroprene sealant.

2.8.1 Protection plate: Each corner of the roof in the vicinity of top corner fitting is reinforced by 3.0-mm thick rectangular steel plate to prevent the damage caused by mishandling of lifting equipment.

2.9 Top side rail: Each top side rail is made of a 60- $\times$  60- $\times$  3.0-mm thick square hollow-section steel.

2.10 Side wall: The trapezium section side wall is constructed with 1.6-mm thick fully vertically continuous corrugated steel panels at the intermediate area and 2.0-mm thick fully vertically continuous corrugated steel panels at both ends, which are butt welded together to form one panel and continuously welded to the side rails and corner posts. All overlapped joints of inside are caulked with chloroprene sealant.

2.11 Front structure: Front end structure will be composed of one bottom end rail, two corner posts, one top end rail, four corner fittings and an end wall, which are welded together.

2.11.1 Bottom end rail: The bottom end rail to be made of a 4.0-mm thick pressed open section steel is reinforced by three internal gussets. A 200- $\times$  75-mm panel is cut out at each end of the bottom end rail and reinforced by 200- $\times$  75-mm channel steel as a protection against handling equipment damages.

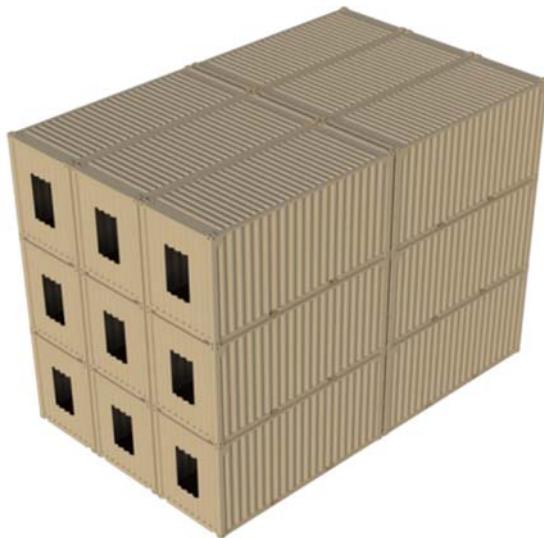
2.11.2 Front corner post: Each corner post is made of 6.0-mm thick pressed open-section steel in a single piece, and designed to give a sufficient strength against stacking and racking forces.

2.11.3 Top end rail: The top end rail is constructed with 60- $\times$  60- $\times$  3.0-mm thick square hollow-section steel at lower part and 3.0-mm thick pressed steel at upper part.

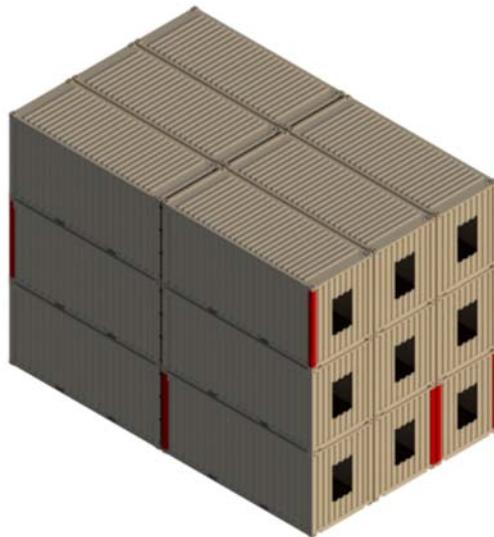
2.11.4 Front wall: The trapezium section front wall is constructed with 2.0-mm thick vertically corrugated steel panels, butt welded together to form one panel, and continuously welded to front end rails and corner posts. All overlapped joints of inside are caulked with chloroprene sealant.

### 3. ANALYSIS CONFIGURATION

To investigate progressive collapse resistance of relocatable barracks construction an analysis phase was first completed. The analysis phase of the project consisted of computer-aided structural modeling with the program CSI SAP2000®. A test article replicating barracks similar to Figure 1 was dictated by the U.S. Air Force to be analyzed and tested. The test article was to be three stories high constructed with CONEX containers in a  $3 \times 3 \times 2$  grid as shown in Figure 3. The column loss locations investigated are shown in Figure 4.

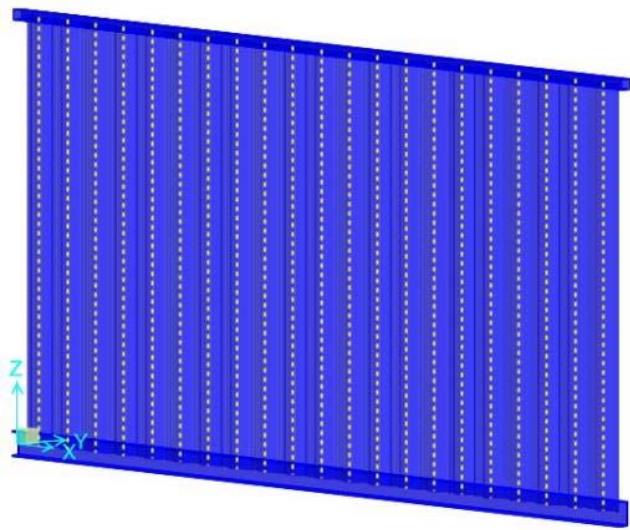


**Figure 3.  $3 \times 3 \times 2$  Test Article Rendering – Isometric View**

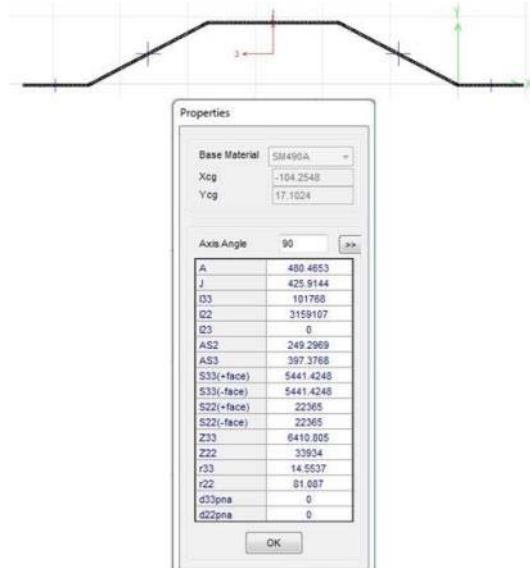


**Figure 4. Column Removal Locations (Shaded Red)**

Each CONEX was modeled in CSI SAP2000® to match drawings and specifications provided by the container manufacturer and listed above. Once the geometry of each component was successfully created, material definitions were applied. After part geometry and material applications were defined boundary conditions for each part were applied. Fabricator drawings indicate all frame members to include corrugated metal sheets are fully welded at ends so fixed-end constraints were used. Corner castings were not modeled explicitly for this scope of work but frame end reactions and stresses were monitored to ensure no casting failure was likely to occur. Corrugated sheathing geometry was modeled by constructing 30.48-cm long segments and fixing them top and bottom to the structural frame as shown by the dashed lines in Figure 5. Each corrugated sheathing segment was modeled as fully fixed at the ends and fully unrestrained for all buckling modes for conservatism and an added factor of safety for testing purposes. There was no contact definition applied between corrugated sheathing segments, which means the segments behaved as individual columns with the properties shown in Figure 6.

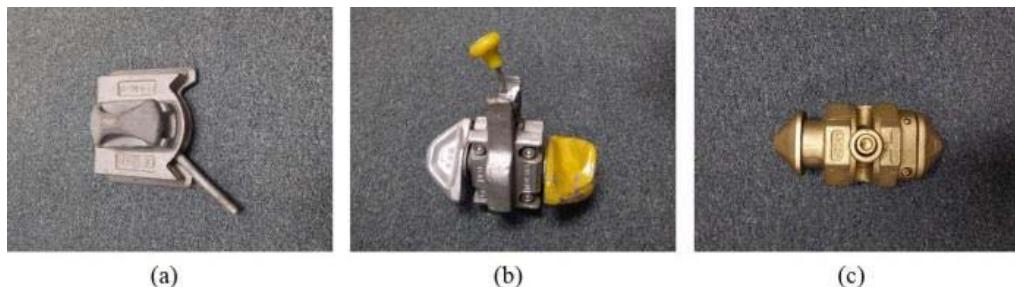


**Figure 5. Corrugated Sheathing Elements**



**Figure 6. Corrugated Sheathing Segment Section Properties (KN, mm)**

Twistlocks were not modeled explicitly due to their complex part makeup. Common twistlocks are shown below in Figure 7. Twistlocks are designed to be used for containers stacks on ocean-going vessels, consequently twistlocks typically have to meet strength demands of fully loaded container experience g-force accelerations due to listing, yawing, and impact forces associated with ocean travel. The inherent



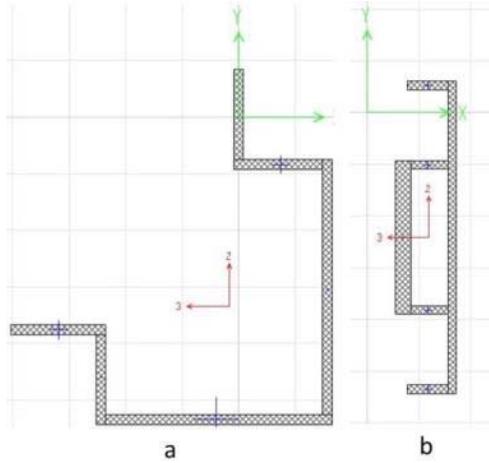
**Figure 7. (a) Weldable Base Twistlock (b) Vertical Twistlock (c) Horizontal Twistlock**

strength of the twistlocks gave confidence in the approach of modeling the vertical and horizontal twistlocks as rigid links. Inside CSI SAP2000® reactions and stresses at the links are easily monitored for comparison to twistlock manufacturer stamped capacity to determine validity of each model. Weldable base twistlocks were modeled as pinned connections inside CSI SAP2000®.

CONEX containers have four corner posts, each corner post carrying approximately 25% of the total CONEX floor and roof tributary areas. Corner posts are constructed by rolling sheets of steel into the shapes shown in Figure 27. The corner posts have stiffeners welded to help prevent local buckling. To ensure a conservative analysis corner post stiffeners were not modeled in CSI SAP2000® and section modeling and properties are shown by Figure 9.



**Figure 8. (a) Front Corner Post (b) Rear Corner Post**



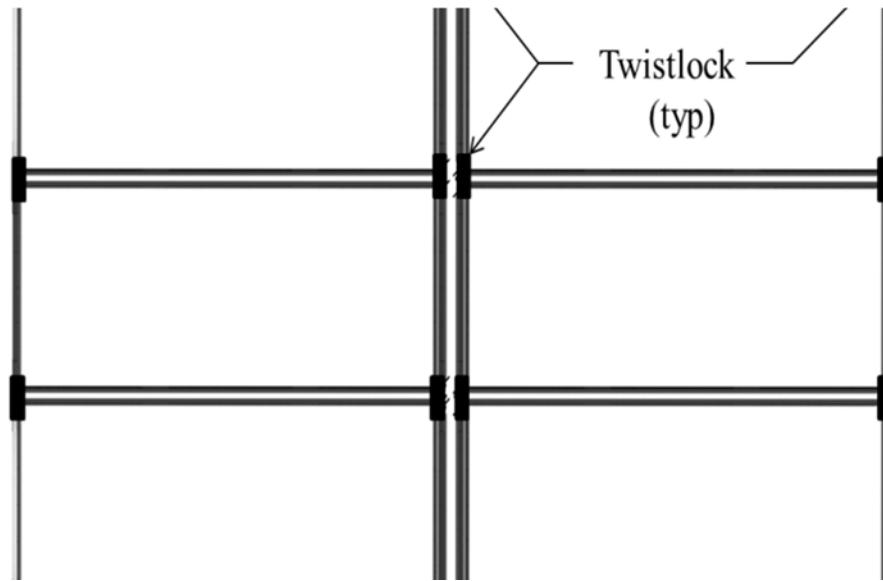
**Figure 9. Section Designs for Corner Posts with CSI SAP2000® (a) Front Corner Post (b) Rear Corner Post**

Fielded relocatable barracks typically utilize a combination of twistlocks and tie-force plates that aid in connecting containers to each other. However, due to concerns over whether the tie-force plate was present in each relocatable barracks this feature was ignored. Ignoring the tie-force plate reduces the overall stiffness of the structure by some amount but yields a conservative approach. The tie-force plate of discussion is shown in Figure 10 installed on a relocatable barracks currently in theatre.



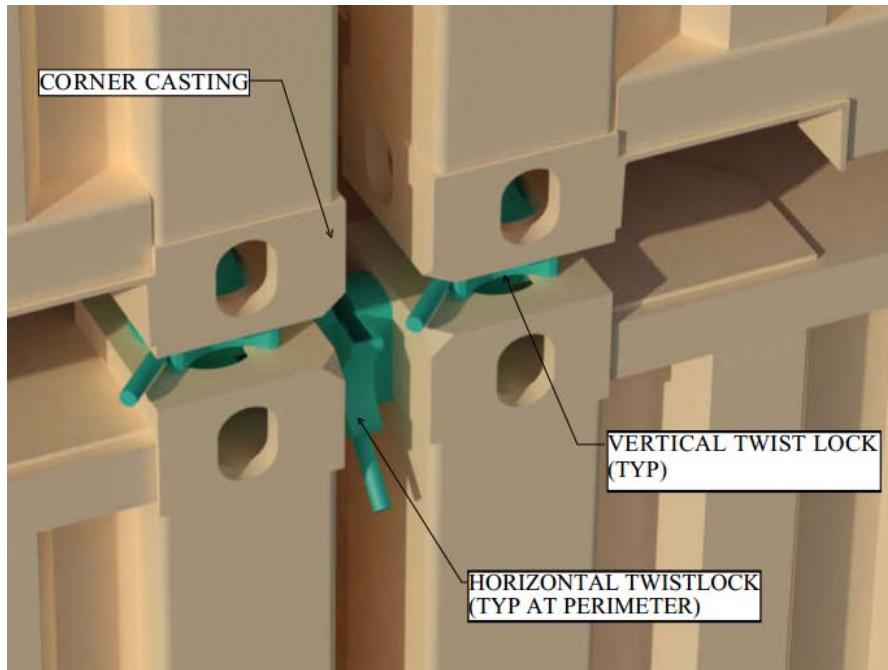
**Figure 10. Tie–Force Plate Approximately 12.7 mm Thick of Unknown Grade**

Twistlock connection schemes vary and can be detailed to meet a specific strength requirement for a given container stack. For relocatable barracks each twistlock acts as a tie–force transfer in the event of column loss but also allows a relocatable barracks to behave similar to a typical structural connection found in buildings. Containers were connected to each other according to the schematic shown below in Figure 11 and Figure 12 for the purposes of this study. The connection scheme chosen reflects that of a relocatable barracks currently in theater. At each level of the structure a horizontal twistlock at each container top casting was utilized while a vertical twistlock occurs at every corner post top casting to corner post bottom casting in the structure.

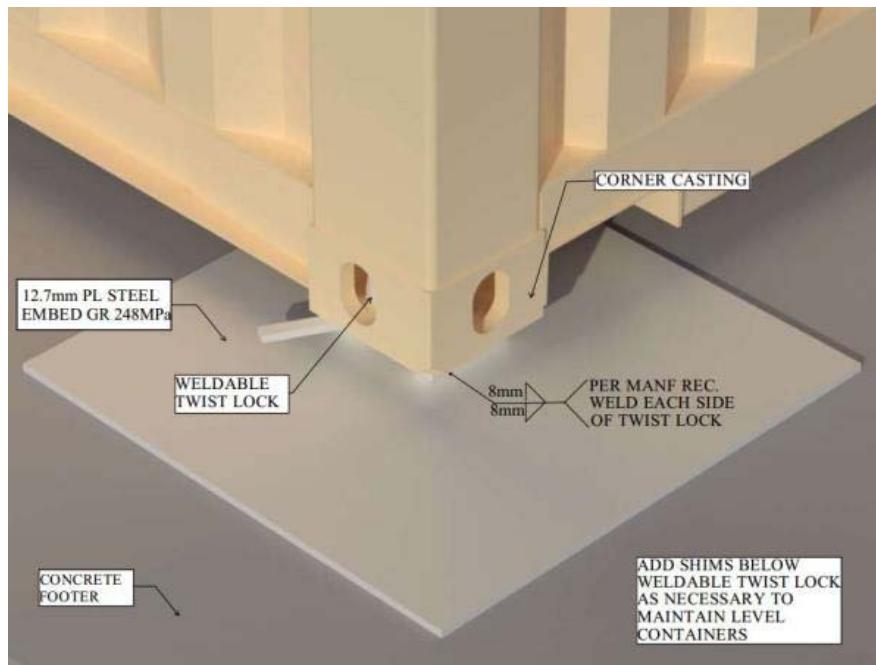


**Figure 11. CONEX Twistlock Scheme Top View (Floors and Roof Hidden)**

Ground level CONEX containers typically are lowered onto a base twistlock, which engages the lower corner column casting. The base twistlock in the relocatable barracks under investigation was welded to 12.7-mm thick Gr. 248-MPa steel baseplate with an 8-mm fillet weld on both sides of the twist lock as shown in Figure 13. For marine applications the base twist lock is either welded or mechanically fastened to a ship deck—this method is not discussed in this paper.



**Figure 12. Typical Container Twistlock Connections**



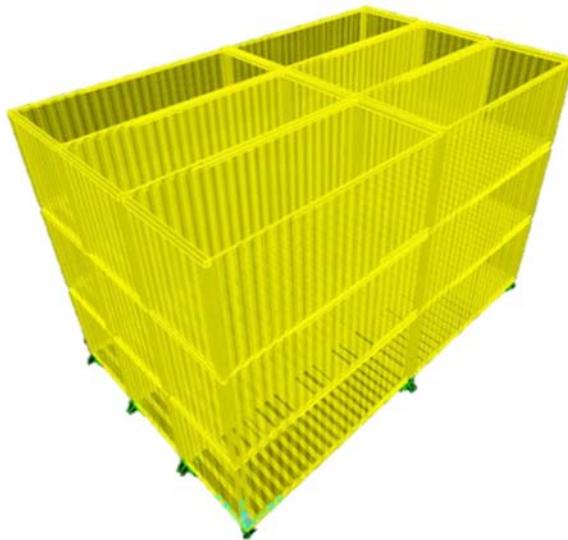
**Figure 13. Weldable Twistlock to Baseplate Detail**

After geometry and boundary conditions were defined, load was applied to the model. Dead load, live load, and environmental load data (Table 1) per governing criteria<sup>3</sup> for the location of Tyndall Air Force Base, Florida, which is where the relocatable barracks test article was to be constructed, were applied. Initial gravity-only analysis models were created and column load takedowns were performed by hand then checked against CSI SAP2000® results to ensure proper agreement. A fully constructed model is shown in Figure 11.

**Table 1. Loading Criteria**

Loading Type	Magnitude	Origin
Dead Load	Self-Weight	ASCE7-10
Superimposed Dead Load	0	N/A*
Floor Live Load	2.4 kPa	AFCEC
Roof Live Load	0.96 kPa	AFCEC
Wind Velocity (3-s gust)	64.4 m/s	ASCE7-10

\*N/A denotes not applicable

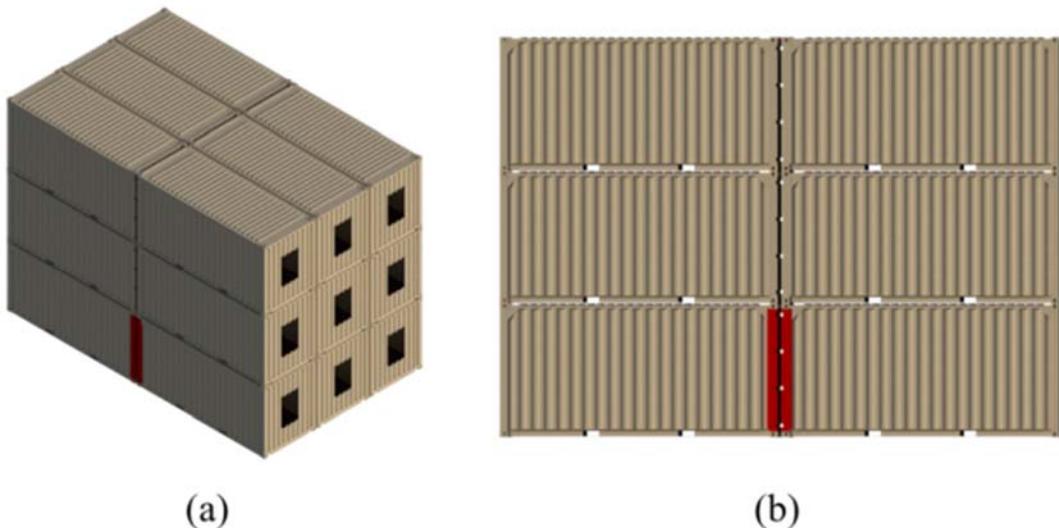


**Figure 14. CONEX Relocatable Barracks Test Article CSI SAP2000® Model**

#### 4. ANALYSIS RESULTS

The UFC indicates a load combination of  $1.2 D + 0.5 L$  for progressive collapse; however, for test safety an increase over UFC load was utilized. Rather than  $1.2 D + 0.5 L$ , a load combination of  $1.2 DL + 1.6 LL$  for stresses and  $1.0 DL + 1.0 LL$  for deflection checks was utilized. Where CONEX corner posts at the same level are connected to each other it was assumed that an incoming explosive threat would realistically destroy both corner posts in that immediate area and were analyzed accordingly. For brevity each individual column location will not be discussed.

In lieu of describing in detail each column removal location, for brevity the most severe deflection inducing column removal location will be discussed. The reader should note that each column removal investigation proceeded in exactly the same fashion as described here. Column removal location shown by Figure 15 was analyzed by simply deleting the corner posts at that location and applying the load combination of  $1.2 DL + 1.6 LL$ . Internal loading to columns of interest were noted and a new model was created to allow a ramp function to capture inertial effects. To appropriately determine the time step required for ramping load to zero the fundamental period of the damaged structure was noted by running a modal analysis in CSI SAP2000®.



**Figure 15. Worst-case Column Removal Location (a) Iso View (b) Elevation View**

The model showed very little deflection and no excess stress concerns for the column removal location shown in Figure 15. Maximum deflection was approximately  $1/8$  in. With high confidence in the model results, the decision was made to proceed with construction and testing of a real world test article to verify modeling assumptions.

## 5. TEST ARTICLE CONSTRUCTION

For this program CONEX containers were purchased that adhered to the specifications listed above to match exactly the CONEX containers used in military barracks. The containers were shipped to Tyndall Air Force Base complete with cargo worthy “Grade B” certificates from the seller. Each container was unaltered with minor dents, scratches, and rust (Figure 16).



**Figure 16. CONEX Container General Condition upon Delivery to Tyndall AFB**

Containers were unloaded and stored at the Sky X blast testing range at Tyndall AFB for a short period of time before structural modifications occurred. To replicate more closely a relocatable barracks structure, the decision was made to cut a window opening of 137 cm x 91.4 cm, similar to those found on barracks facilities currently deployed throughout the world (Figure 17).



**Figure 17. Window Opening Cut out by AFCEC Contractors**

After window openings were cut, column splices were to be incorporated into container posts where column removal tests were to occur. AFCEC contractors at Tyndall AFB chose to simulate column loss in a controlled fashion by utilizing a hydraulic structure jacking system. The concept was to simply replace a spliced section of column with a hydraulic jack for testing, then replacing the column splice segment after the test was complete similar to Figure 18 and Figure 19.



**Figure 18. Hydraulic Jacking Detail for Test**



**Figure 19. Column Splice Rendering**

The center of gravity for both the corner posts and the hydraulic jack were aligned to avoid any eccentric loading.

Hydraulic jacking allowed controlled opening and closing of hydraulic valves while simultaneously monitoring hydraulic pressure as well as the ability to quickly release all hydraulic pressure and simulate sudden column loss. The structure jacking system chosen is referred to as a crib jack and is shown in Figure 20.



**Figure 20. Hydraulic Crib Jack**

The crib jack system has a capacity of 69 MPa and as applied pressure was expected to be in the range of 34.5 MPa or less the factor of safety was satisfactory for use in the test apparatus. CONEX container stacks are erected by any number of methods. Corner post splicing was accomplished by torch cutting the post and grinding smooth the torch cut area. After torch cutting and grinding operations were complete a column splice plate was welded to each of the

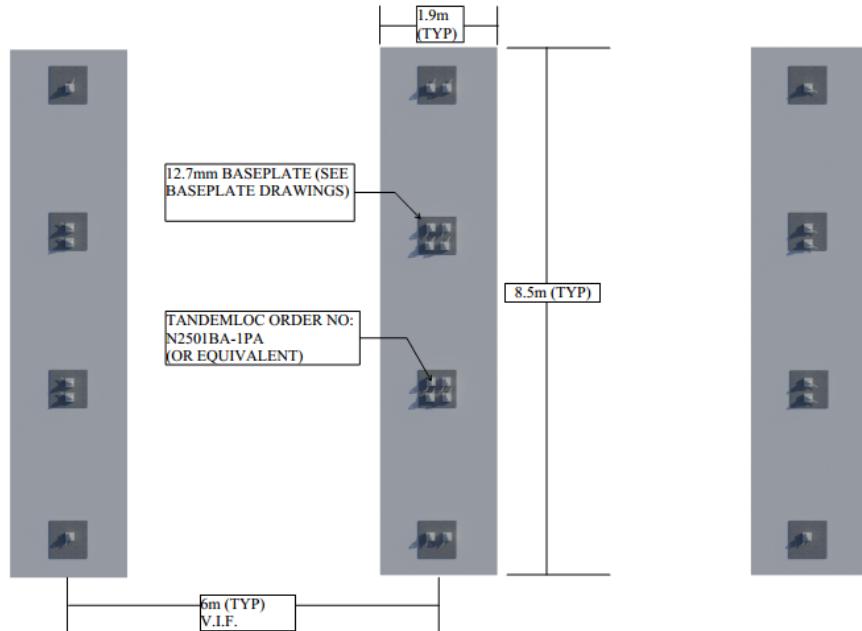
corner posts and also to the removed section (Figure 21).



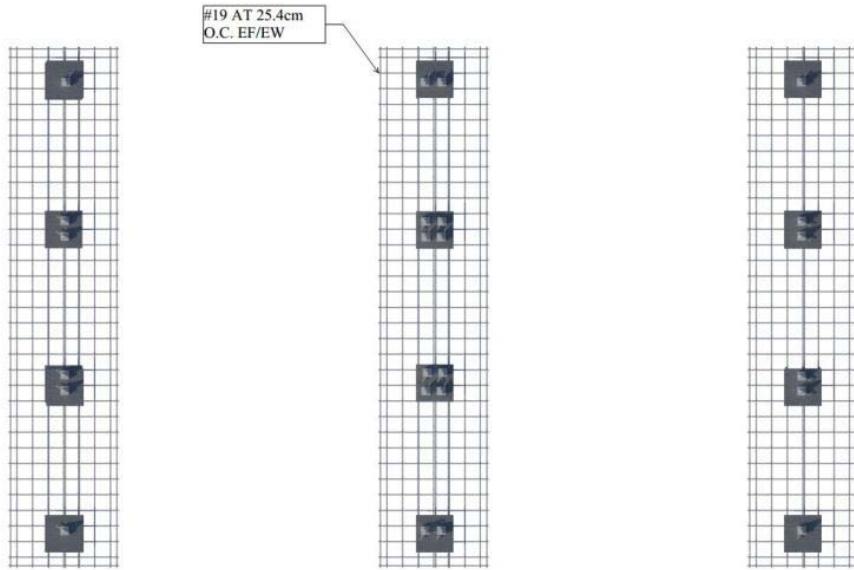
**Figure 21. (a) Typical Rear Corner Post Splice (b) Typical Front Corner Post Splice**

Once column splices were completed the same splice plate was also welded to the top and bottom of the hydraulic jacks to allow testing activities.

Due to the sandy soil conditions and shallow water table at Tyndall AFB's Sky X test range, spread footers were elected to serve as a foundation for the relocatable barracks test article. The foundation was designed and constructed by AFCEC contractors. Engineering analysis determined that each concrete footer would need to be 1.9 m (wide)  $\times$  8.5m (long)  $\times$  45.7cm (thick), arranged approximately as shown in Figure 22 with the rebar layout shown in Figure 23.



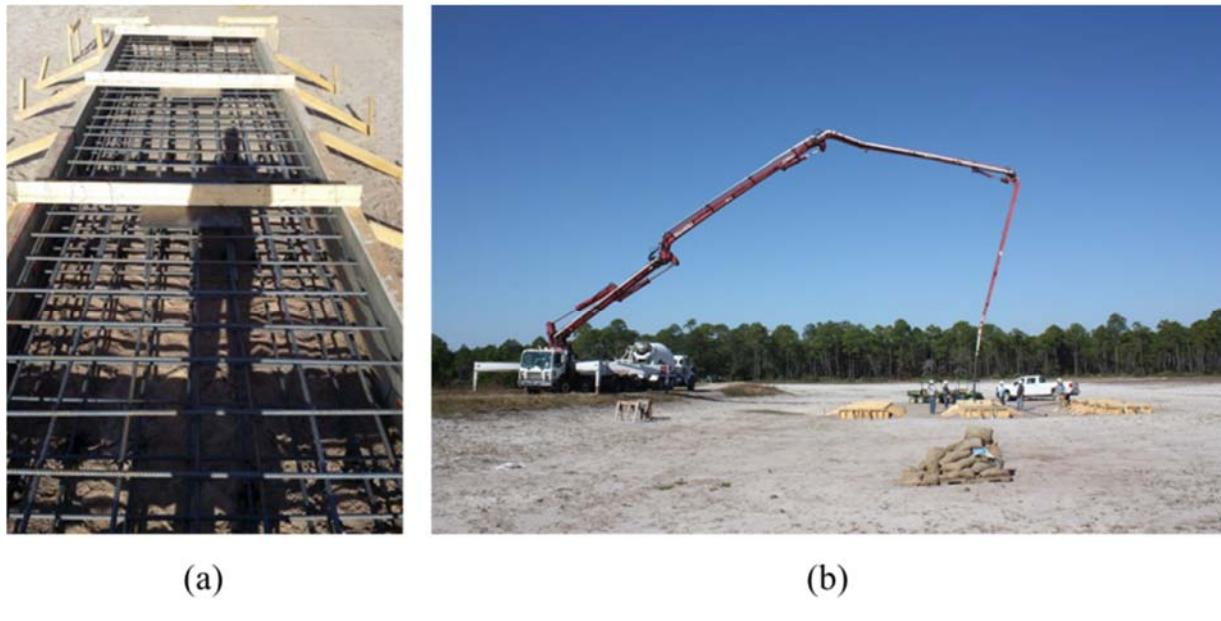
**Figure 22. Foundation Plan View**



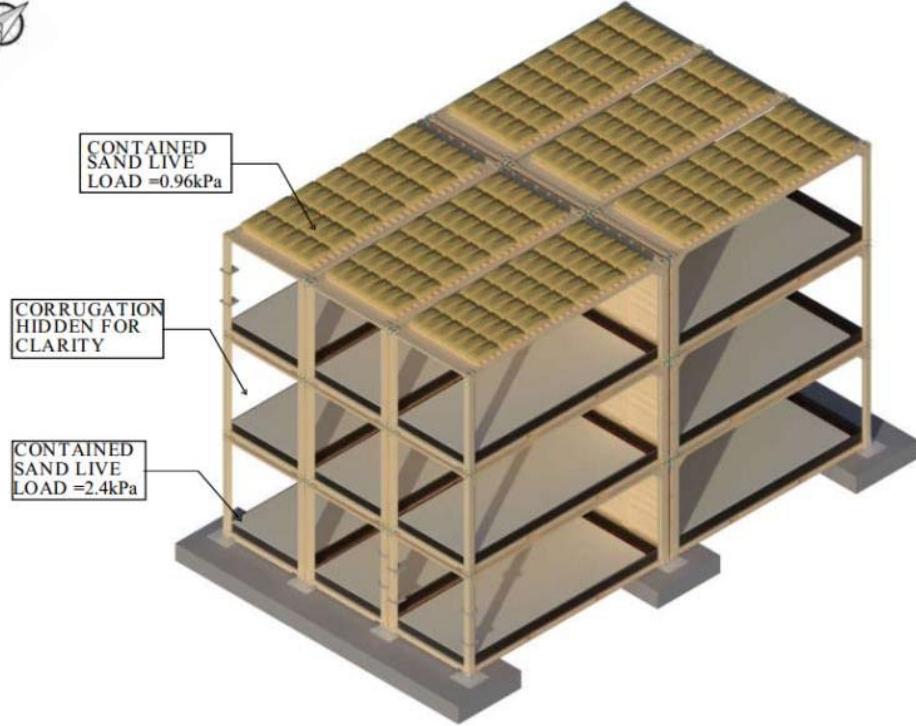
**Figure 23. Rebar Layout Plan View**

Foundations were then formed and poured by AFCEC contractors and allowed to cure until concrete strength was above 20.7 MPa before erecting containers. A crew of four men was used to form and pour the footers and the decision was made to utilize a pump truck to allow easier concrete placement Figure 24.

Before beginning erection of the relocatable barracks, a method of simulating live load needed to be developed. It was determined that, due to the nature of the test site, sand would be a good method of simulating live loads. Sand from a nearby stockpile was tested for density and a subsequent sandbox was designed. The density drove the depth the sandboxes were required to be to appropriately simulate floor and roof live loads (Figures 25 and 26). Initially sandbags were to be used for the roof; however, due to time required to fill sand bags the decision was made to build sandboxes for the roof as well.



**Figure 24. (a) Formed Concrete Spread Footer (b) Pump Truck Extended to Spread Footers**



**Figure 25. Rendering of Sand Simulating Live Loads**

Once sand loading operations were completed, erection of the relocatable barracks test article could begin. An AFCEC-owned crane was chosen as the best piece of equipment for placement of each CONEX. Use of a crane to fly a CONEX at an angle for more precise placement proved critical to ensure CONEX-to-CONEX connections could be made. A general construction sequence is illustrated by Figure 27 and a completed stack is shown in Figure 28.



**Figure 26. Sand Being Loaded into Sandbox**



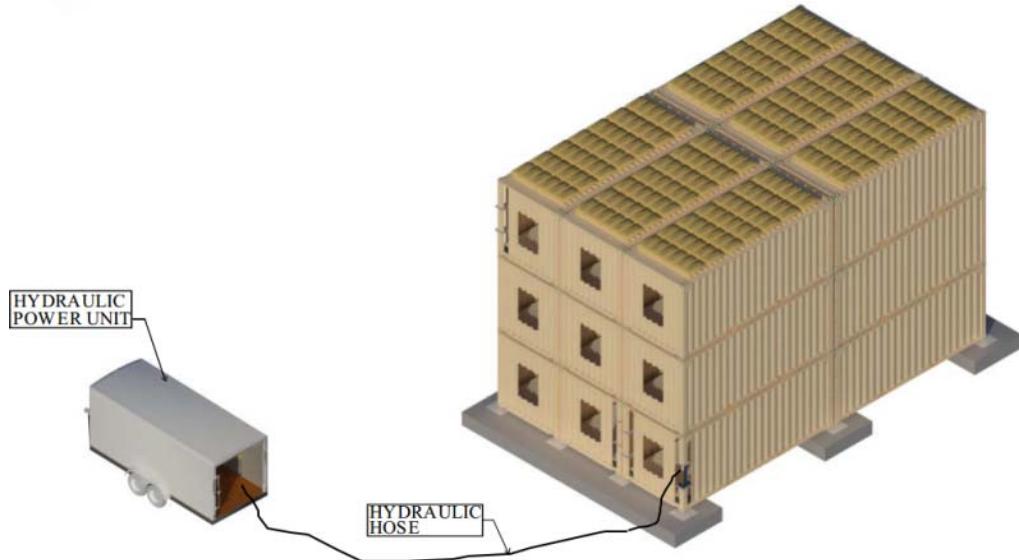
**Figure 27. Construction Sequence**



**Figure 28. Completed Relocatable Barracks Test Article**

## 6. COLUMN REMOVAL TESTING

Column removal tests were completed with the use of an AFCEC-owned hydraulic structure jacking system. The hydraulic power unit was housed in a trailer and stationed near the relocatable barracks, similar to Figure 29. For each test location hoses were simply attached to the jacks from the hydraulic power unit and jack operation was controlled from the hydraulic power unit trailer.



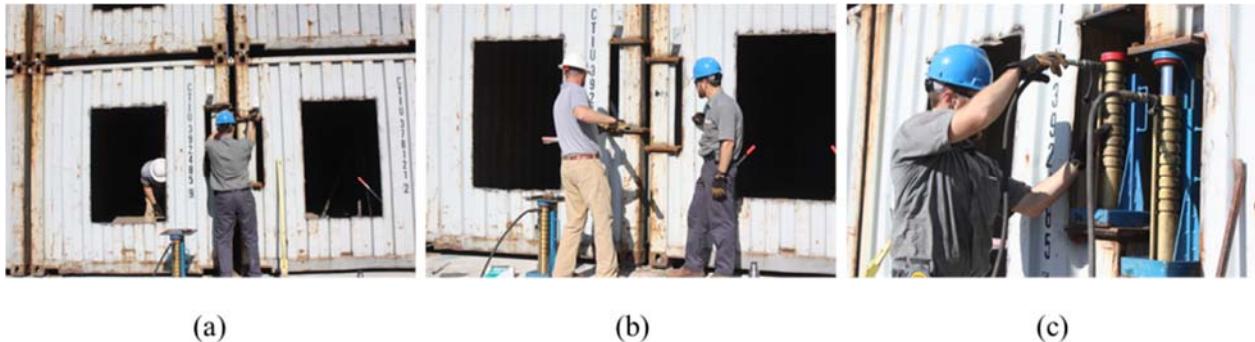
**Figure 29. Hydraulic jack schematic set up**

Close monitoring of hydraulic pressures could be achieved for each individual jack through a manifold with gauges and control valves for up to 11 hydraulic jacks simultaneously. High definition cameras were also set up to monitor the structure for each column removal test (Figure 30).



**Figure 30. Hydraulic power unit**

For each test, shoring was first installed in immediate proximity to the column removal location. After shoring was installed the column splice segment was unbolted and removed and a hydraulic jack was inserted; however, at the top plate connect the nuts were left off the bolts to allow the jack to retract without “pulling” the structure with it. Once hydraulic pressure began to build and indicate that load was on the jack and off the shoring the shoring was removed. Hydraulic pressure was then quickly released by opening the valves quickly. Time of drop for hydraulic pressure was measured as less than  $1/10 \times$  the fundamental period of the structure so as to impart inertial effects. This method of column testing was agreed on by all parties as sufficient to replicate the “instantaneous loss” of a corner post and each test proceeded in the same fashion. A test sequence is shown in Figure 31.



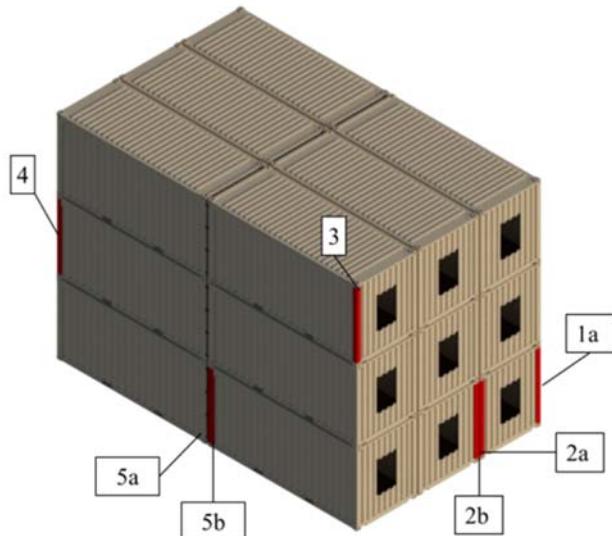
**Figure 31. (a) Shoring Installed (b) Column Segments Removed (c) Hydraulic Jacks Inserted**

Column removal tests showed very little deflection. Deflection measurements were obtained by simply measuring the distance between corner post plates before the test and then again when jacks were retracted. Table 2 shows results of the hydraulic testing; refer to figure 32 for column locations.

**Table 2. Column Removal Test Results**

Name	Column Location	Total Deflection, mm
Bottom Right Corner	1	1.6
Bottom Right Double	2a	1.6
Bottom Right Double	2b	1.6
3rd Floor Corner	3	3.18
2nd Floor Corner	4	3.18
Bottom Door	5a*	4.76
Bottom Door	5b*	1.6

\*Maximum deflection recorded at this location



**Figure 32. Column Removal Test Location Nomenclature**

## 7. EXPLOSIVE TEST

Once hydraulic testing was completed, and the worst-case column removal location was identified, a blast testing phase was executed. The explosive devise chosen for this test was a 155-mm artillery shell. AFCEC chose this round because it is indicative of a threat that may be presented to a relocatable barracks structure in theater. A 155-mm artillery shell weighs 43.2 kg, is approximately 800 mm long and contains 15.8% explosive by weight. The 155-mm artillery shell was mounted to the relocatable barracks in same location as 5a and 5b from Figure 32 on the opposite face (Figure 33).



**Figure 33. 155-mm Artillery Shell Placement**

The 155-mm artillery shell was then fired statically with the use of a detonator and firing line from a safe distance. The test was recorded with high-speed cameras as well as 4k-resolution real-time cameras. The damage to the relocatable barracks was significant. The corner posts and the twistlocks in the region of the detonation experienced a total loss of structural integrity as indicated by Figure 34.



**Figure 34. Damage to Barracks from Detonation of a 155-mm Artillery Shell**

Post-test measurements revealed that the bottom corner castings immediately above the damaged columns shown in Figure 34 had permanent downward deflection of approximately 23.8 mm. The relocatable barracks exhibited no signs of impending collapse and were left untouched for monitoring for a number of weeks with no change in deflections and therefore can be assumed to be stable.

## 8. CONCLUSIONS

AFCEC contractors were able to successfully demonstrate progressive collapse resistance by completing a rigorous analysis and testing program. Phase 1 analysis demonstrated through

structural modeling the ability of CONEX-based relocatable barracks to redirect load safely due to a column loss. Phase 2 validated those analytical models through a series of controlled hydraulic column removal tests. Finally, Phase 3 proved that when a column location is destroyed due to detonation of a 155-mm artillery shell, relocatable barracks will survive and maintain enough structural rigidity to preclude any progressive collapse concerns. It is the recommendation of the authors that designers of CONEX-based relocatable barracks facilities limit corrugated sheathing removal whenever possible as the presence of corrugated steel greatly stiffens the structure. Designers should also pay close attention to twistlock placement and ensure they are properly installed to properly connect the containers together and allow proper load redistribution upon loss of a column.

## **LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS**

AFCEC	Air Force Civil Engineer Center
CONEX	Container Express
ISO	International Organization for Standardization
KN	Kilo newton
Gr.	Grade
D	Dead Load
L	Live Load